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AUTHOR Selleck, Ben: Espy, John
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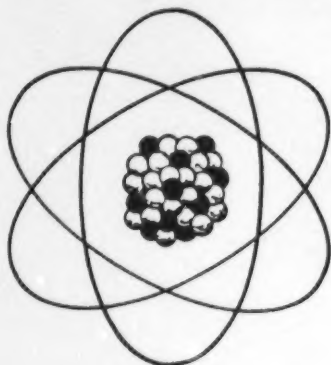
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ABSTRACT

This first in a series of eight modules for a course titled Metrology describes the fundamentals of metrology as they pertain to dimensional inspection. The module follows a typical format that includes the following sections: (1) introduction, (2) module prerequisites, (3) objectives, (4) notes to instructor/student, (5) subject matter, (6) materials needed, (7) procedures, (8) data table, (9) reference materials, (10), test. (The course is one of fifteen technical courses for the second year of a two-year postsecondary curriculum in Nuclear Quality Assurance/Quality Control Technology.) (LRA)

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COURSE 27 METROLOGY

MODULE 27-1 Fundamentals of Metrology



GENERAL PHYSICS CORPORATION
Columbia, Maryland

CE 024 253



COURSE MODULES

COURSE 27 METROLOGY



- Module 27-1 Fundamentals of Metrology
- Module 27-2 Fixed Gages, Dividers, Calipers and Micrometers
- Module 27-3 Gage Blocks, Mechanical Comparators and Electronic Comparators
- Module 27-4 Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
- Module 27-5 Tolerancing
- Module 27-6 Calibration
- Module 27-7 Statistical Techniques in Metrology
- Module 27-8 The Total Measurement System

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This module was prepared for General Physics Corporation by Ben Selleck, Ben-Sel Associates, and John Espy, General Physics Corporation.



GENERAL PHYSICS CORPORATION

1979



INTRODUCTION

Metrology is a science of measurement that is concerned with accurate and reliable measurements. While metrology deals with all units of measurement, this course pertains to dimensional inspection.

Some thought provoking questions can quickly be brought to mind when considering dimensional inspections. Considering a wood or steel ruler that is scribed in inches and is twelve inches long, a number of questions can be asked. What is the basis for the length that is termed one foot or one inch? Of the millions of twelve inch rulers in existence, is each exactly one foot? Is the scale of each uniformly scribed? Will each give the same measurement results? Are there any environmental effects on the measurement results? Is a scale of 1/32 inch increments more readable than a scale of 1/64 inch increments? Should fractions or decimals be used to indicate portions of an inch? When should a device more accurate than the ruler be selected for the measuring instrument?

This module describes the fundamental concepts on which answers to these types of questions are based. This module presents basic theory of measurements. Later modules of this course describe the application of these concepts to specific measurement devices and procedures.

The Nuclear QA/QC Technician has an important role with respect to metrology. This role is in relation to the dimensional inspector who makes measurements and the calibration technician who sets the accuracy of measuring devices. This course as a whole is designed to equip the student/trainee to perform the following tasks of the Nuclear QA/QC Technician:

- Prepare inspection procedures that describe the measuring device, specific techniques, and records to be used.

- Prepare sampling inspection plans.
- Investigate and report the sources of error in measurements and actions to reduce error.
- Monitor or audit inspection functions.
- Monitor or audit calibration functions.



MODULE PREREQUISITES

None.



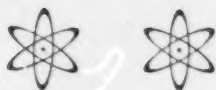
OBJECTIVES

Upon completion of this module, the student/trainee can:

1. State two reasons that metrology must be applied to the design, construction and operation of nuclear power plants.
2. Define the following terms:
 - a. Standard
 - b. Accuracy
 - c. Precision
 - d. Readability
 - e. Sensitivity
 - f. Linearity
 - g. Measurement
 - h. Tolerance
3. Describe the role of standards in a measurement process.
4. Describe the hierarchy of standards.
5. State the purpose of the sensors, transducers, and

readout.

6. List the two principles that govern the accuracy of a measurement.
7. Name four factors that affect precision of a measurement process.
8. Discuss the use of a tolerance-to-readability ratio.
9. Name the factors that affect the sensitivity of a measuring device.
10. Name the factors that affect the readability of a measuring device.
11. Distinguish between systematic error and random error.
12. Name six sources of errors that affect accuracy and describe contributing factors.
13. Demonstrate ability to detect errors in a linear measurement with a rule or scale.



SUBJECT MATTER

FUNDAMENTALS OF METROLOGY

Need for Metrology

Dimensional metrology had its origins when humans began to develop products, goods and services to meet life's needs. It was soon recognized that established rules must be set in order to ensure fit and function of products. That is to say, some type of dimensional control would have to be established to allow component parts to fit correctly during assembly and function properly when installed and subsequently tested. In addition to the concept of fit and function was the basic idea of interchangeability of parts and components. It became clear that standards needed to be established to ensure proper duplication of components.

The need for ensuring fit, function, and interchangeability is apparent when envisioning the complexities of a nuclear power plant. The nuclear power plant is comprised of some 80 to 100 major systems and represents an investment in 1978 of about \$1,000,000,000. Each major system consists of subsystems and components. Certain components can cost a few million dollars each. Thousands of vendors are involved with the manufacture and installation of these components, subsystems, and systems. With all of the complexities, the end result must be the integrated operation of all systems, such that power is safely produced and transmitted to consumers. This task would be impossible without metrology. For example, a relatively simple component such as a valve, involves numerous vendors and complexities. As shown in Figure 27-1-1, a valve manufacturer who performs practically all processing and assembly of parts of a valve still relies on several other vendors for raw materials and certain parts. Frequently, some of the pro-

cessing steps shown for the valve manufacturer are subcontracted to additional vendors. Dimensional control is absolutely necessary if all the parts are to fit at assembly and function properly at test and after installation.

The valve shown in Figure 27-1-1 is a type that is bolted to flanged pipe when installed. It is not difficult to imagine the consequences of an out of alignment condition of the bolt holes in the valve body and the pipe flanges. Since redrilling the bolt holes would probably not leave sufficient material between the holes, either new flanges or a new valve body would be needed. This type of concern for fit-up at installation is compounded by the more complex components, such as a reactor pressure vessel. The reactor pressure vessel has external interfaces with support mounts, reactor coolant piping, a closure head, and other piping systems. Misorientation of any of these interfaces can result in hundreds of thousands of dollars in repair costs.

These few illustrations of interfacing dimensions and the concept of interchangeability show that metrology is absolutely necessary to protect the investment by each vendor supplying hardware and by the ultimate owner, the nuclear utility.

UNITS OF MEASUREMENT

Units

What is a unit? People use units throughout their lives without necessarily realizing it. For example, if a person wished to meet a friend at a certain place and a given time, it would be confusing if units were not used in the conversation. For example, one might say "I will see you in 2 ____ at the restaurant which is 25 ____ up the road." Although one may guess what the units might be, there would still be some doubt. For example, is the meeting to be

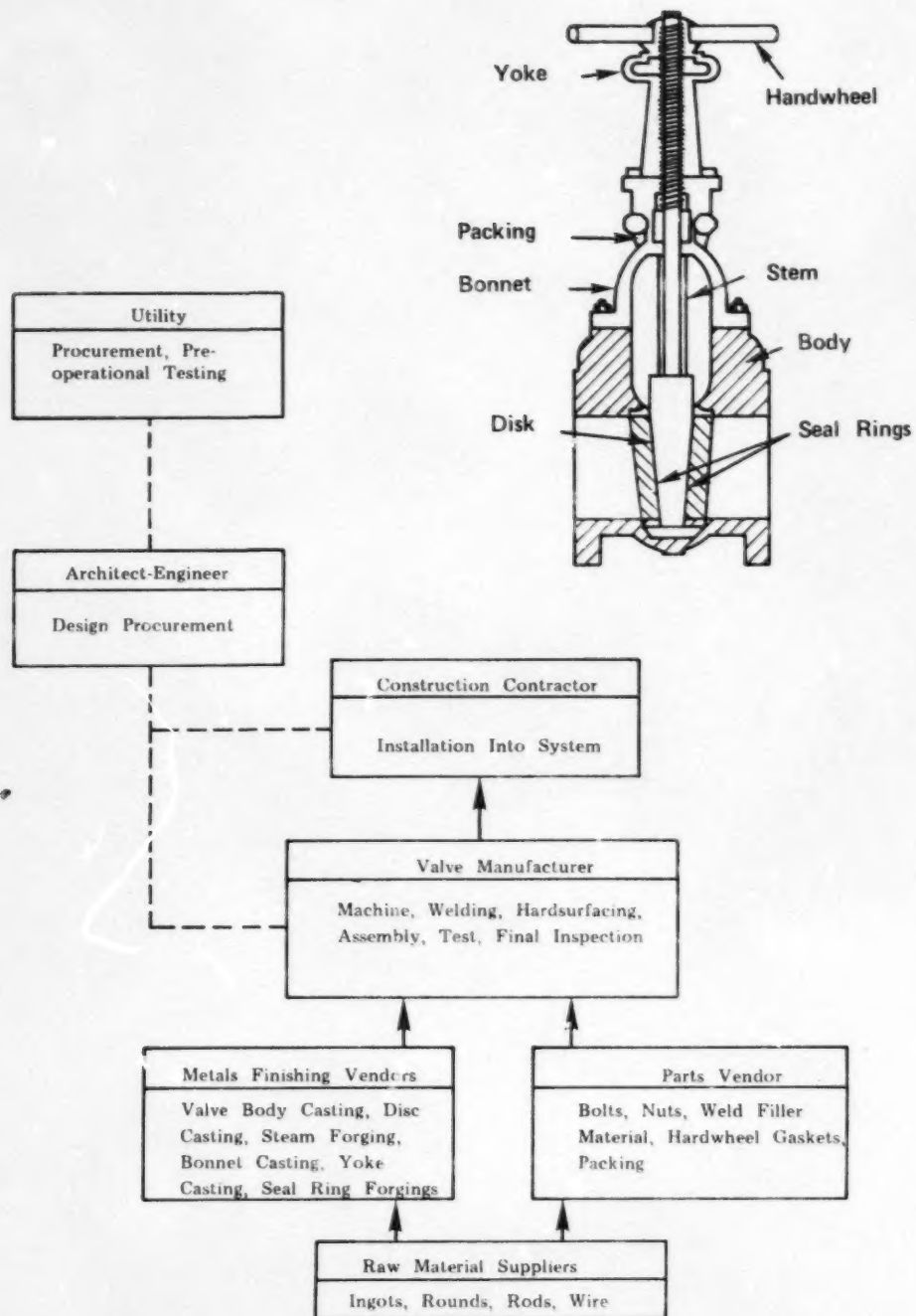


Figure 27-1-1. Vendor Interfaces

held in 2 minutes or 2 hours? Is the restaurant 25 feet or 25 miles up the road? These clarifying terms are called units.

Definition of a Unit

A unit is a determined quantity that has been adopted as a standard of measurement. It is used to inform us of how much of a quantity we are working with. Examples of units are feet, inches, centimeters, pounds, kilograms, gallons, grams and seconds. In general, a unit is fixed by definition and is independent of physical conditions such as temperature and pressure.

Development of Some Customary Units

It is not the intent of this module to describe the development of units. However, a brief discussion on development of units of length should assist the student/trainee to appreciate the need for standardization of units of measurement.

The cubit was the first recorded unit used by ancient people to measure length. There were several cubits of different magnitudes that were used. The common cubit was the length of the forearm from the elbow to the tip of the middle finger. It was divided into the span of the hand (one-half cubit), the palm or width of the hand (one-sixth), and the digit or width of a finger (one twenty-fourth). The Royal or Sacred Cubit, which was 7 palms or 28 digits long, was used in constructing buildings and monuments and in surveying. The inch, foot, and yard evolved from these units through a complicated transformation not yet fully understood. Some believe they evolved from cubic measures; others believe they were simple proportions or multiples of the cubit. In any case, the foot was inherited from the Egyptians by the Greeks and

Romans. The Roman foot was divided into both 12 unciae (inches) and 16 digits. The Romans also introduced the mile of 1,000 paces or double steps, the pace being equal to 5 Roman feet. The Roman mile of 5,000 feet was introduced into England during the occupation. Queen Elizabeth, who reigned from 1558 to 1603, changed by statute the mile to 5,280 feet or 8 furlongs, a furlong being 40 rods of $5\frac{1}{2}$ yards each.

The introduction of the use of the yard as a unit of length came later, but its origin is not definitely known. Some believe the origin is the double cubit, others believe that it originated from cubic measure. Regardless of its origin, the early yard was divided by the binary system into 2, 4, 8 and 16 parts called the half-yard, span, finger, and nail. The association of the yard with the "gird" or circumference of a person's waist or with the distance from the tip of the nose to the end of the thumb of Henry I are probably standardizing actions, since several yards were in use in Great Britain.

The need for a single worldwide coordinated measurement system was recognized over 300 years ago. After several attempts by various persons in the sixteen hundreds, the French Academy of Sciences appointed a Commission in 1790 to "deduce an invariable standard for all the measures and all the weights". The Commission developed what has become known as the Metric System of Weights and Measures. The basic unit of length was the meter which was defined as one tenmillionth of the distance from the north pole to the equator along the meridian of the earth running near Dunkirk, France and Barcelona, Spain.

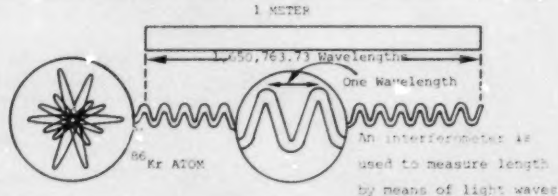
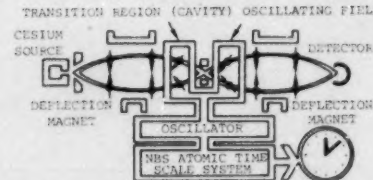
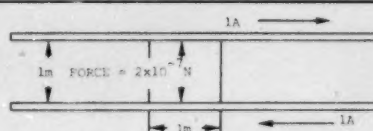
Subsequently, the International Bureau of Weights and Measures located at Sevres, France assigned to its General Conference the responsibility of refining the Metric System. In 1960, the General Conference adopted an extensive

revision and simplification of the Metric System. The new system was termed "International System of Units" which is abbreviated SI for the French "System International". The unit of length remained as the meter, but the definition of meter was based on a number of wavelengths of light emitted by Krypton-86 in a vacuum. Today, the United States National Bureau of Standards bases its definitions of weights and measures on the definitions of the SI System. These SI definitions are given in Table 27-1-1. This table lists the reference standards upon which the basic SI Units are based. It must be emphasized that these are reference standards which allow us to accurately define each of these basic units. These are not to be confused with how the parameters of length, mass, time, etc. are actually measured on the job.

U. S. National Bureau of Standards

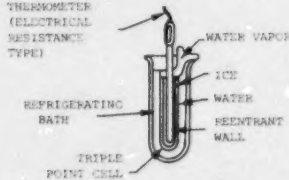
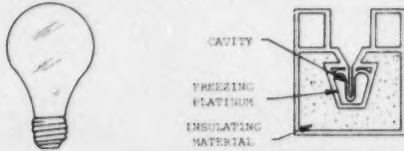
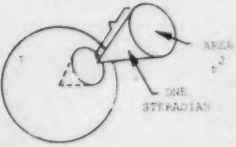
The United States National Bureau of Standards was established by an act of Congress in 1901 to serve as a national scientific laboratory in the physical sciences and to provide fundamental measurement standards for science and industry. The United States developed, from the British System of Weights and Measures, a system of weights and measures that contains both equalities and inequalities with the British System. In both systems, length measurements are identical, e.g., 12 inches = 1 foot, 3 feet = 1 yard, and 1760 yards = 1 international mile. But differences exist with respect to other measures such as dry volume (bushel) and liquid volume (gallon). The U.S. National Bureau of Standards establishes the definition of units within the U.S. System of Weights and Measures and maintains conversion factors to convert any of the U.S. units to their corresponding British and SI units.

TABLE 27-1-1
SI System
Definitions of Fundamental Units of the

Meter	The meter is defined as 1,650,763.73 wavelengths in vacuum of the orange-red line of the spectrum of krypton-86.	
Kilogram	The standard for the unit of mass*, the kilogram, is a cylinder of platinum-iridium alloy kept by the International Bureau of Weights and Measures at Paris. A duplicate in the custody of the National Bureau of Standards serves as the mass standard for the United States. This is the only base unit still defined by an artifact. * Weight is a commonly used term for mass.	 U.S. PROTOTYPE KILOGRAM NO. 20
Second	The second is defined as the duration of 9,192,631,770 cycles of the radiation associated with a specified transition in the cesium-133 atom. It is realized by turning an oscillator to the resonance frequency of cesium-133 atoms as they pass through a system of magnets and a resonant cavity into a detector.	
Ampere	The ampere is defined as that current which, if maintained in each of two long parallel wires separated by one meter in free space, would produce a force between the two wires (due to their magnetic fields) of 2×10^{-7} newton for each meter of length.	

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TABLE 27-1-1 Definitions of Fundamental Units of the SI System (continued)

kelvin (degree Celsius)	The kelvin is defined as the fraction $1/273.16$ of the thermodynamic temperature of the triple point of water. The temperature 0 K is called 'absolute zero'.	The standard temperature at the triple point of water is provided by a special cell, an evacuated glass cylinder containing pure water. When the cell is cooled until a mantle of ice forms around the reentrant well, the temperature at the interface of solid, liquid, and vapor is 273.16 K. Thermometers to be calibrated are placed in the reentrant well. 
candela (lumen)	The candela is defined as the luminous intensity of $1/680,000$ of a square meter of a blackbody at the temperature of freezing platinum (273.15 K).	The SI unit of light flux is the lumen (lm). A source having an intensity of 1 candela in all directions radiates a light flux of 4 - lumens. 
radian (plane angle)	The radian is the plane angle with its vertex at the center of a circle that is subtended by an arc equal in length to the radius.	
steradian (solid angle)	The steradian is the solid angle with its vertex at the center of a sphere that is subtended by an area of the spherical surface equal to that of a square with sides equal in length to the radius.	

This course will use the U.S. System of Weights and Measures. Of most interest are the units of length, area, and plane angles. Conversion factors for these units to the SI System are given in Table 27-1-2.

It is noted that the U.S., England, and Canada reached agreement in 1960 on the standardized conversion of 1 inch equalling exactly 2.54 centimeters. Prior to 1960, differences existed among the three countries on this conversion. Some literature is still in use which reflects such differences. The QA/QC technician must ensure that the most current definitions of units and conversion factors are being used. Periodic publications by the U.S. National Bureau of Standards identify the current definitions of units and conversion factors.

Units of Length International Measure *

Units	Inches	Feet	Yards	Centimeters	Meters
1 inch =	<u>1</u>	0.083 333 33	0.027 777 78	<u>2.54</u>	<u>0.025 4</u>
1 foot =	<u>12</u>	<u>1</u>	0.333 333 3	<u>30.48</u>	<u>0.304 8</u>
1 yard =	<u>36</u>	<u>3</u>	<u>1</u>	<u>91.44</u>	<u>0.914 4</u>
1 centimeter =	0.393 700 8	0.032 808 40	0.010 936 13	<u>1</u>	<u>0.01</u>
1 meter =	39.370 08	3.280 840	1.093 613	<u>100</u>	<u>1</u>

Units	Square Inches	Square Feet	Square Yards	Sq. Centimeters	Square Meters
1 sq. inch	<u>1</u>	0.006 944 444	0.000 771 604 9	<u>6.451 6</u>	<u>0.000 645 16</u>
1 sq. foot	<u>144</u>	<u>1</u>	0.111 111 1	<u>929.030 4</u>	<u>0.092 903 04</u>
1 sq. yard	<u>1296</u>	<u>9</u>	<u>1</u>	<u>3361.273 6</u>	<u>0.836 127 36</u>
1 sq. cm	0.155 000 3	0.001 076 391	0.000 119 599 0	<u>1</u>	<u>0.000 1</u>
1 sq. meter	1550.003	10.763 91	1.195 990	<u>10 000</u>	<u>1</u>

Units of Plane Angles

1 radian = 57.296 Degrees

1 degree = 0.01745 radian

NOTE: Underlined values are exact; others are approximate.

Table 27-1-2. Conversion Factors

STANDARDS

Definitions

There are two types of standards considered in dimensional metrology. One type of standard is the unit of reference by which a given parameter is measured. For example in the SI system, length is measured in meters, mass in kilograms and time in seconds. Table 27-1-1 denotes the precise physical standard by which each of these units is defined. The purpose of these standards is to provide a common reference by which all basic physical parameters, such as length, mass, time, etc., can be compared.

Another type of standard used in dimensional metrology is a rule or authority by which services are provided or a product is manufactured. This second definition of a standard pertains to the written criteria governing products, processes or services.

Hierarchy of Standards for Units

One does not compare all measurements with the corresponding standard given in Table 27-1-1. For example, it is totally impractical to compare all length measurements with the orange-red wavelengths of Krypton-86. It is much more practical for each organization involved in measurements to possess or have ready access to other suitable standards. Accordingly, a hierarchy of standards has evolved as shown in Figure 27-1-2.

Referring to Figure 27-1-2, four divisions of standards are shown. The primary reference standards are those maintained by the U.S. National Bureau of Standards. These standards consist of a duplicate copy of the International Kilogram plus measuring systems that are responsive to the definitions of units given in Table 27-1-1. These standards serve as the common reference for measurements within the

United States for both the SI and U.S. System of Weights and Measures, and, hence, are the primary reference standards.

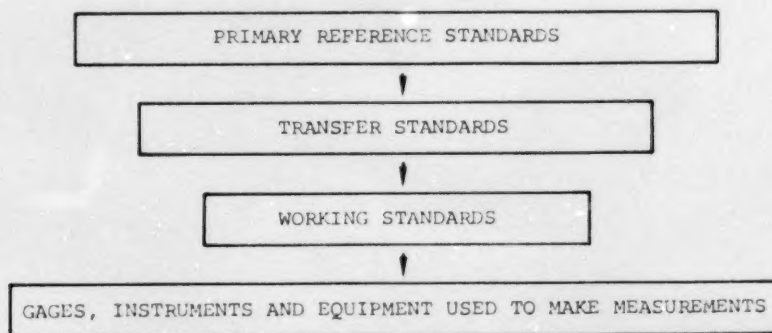


Figure 27-1-2. Hierarchy of Standards

The transfer standards indicated in Figure 27-1-2 are those maintained by industry for the sole purpose of "transferring" accuracy of measurement to the next lower level of standards in the hierarchy. Transfer standards are compared by the National Bureau of Standards with the defined unit of measure. Such a "calibrated" transfer standard may then be used to determine accuracy of other transfer standards of the same fundamental unit of measurement. Economics governs the number of transfer standards in existence. It should be stressed that transfer standards are ordinarily used for calibration and not for actually making measurements of product.

The working standards indicated in Figure 27-1-2 are those possessed by or readily available to every organization that makes measurements of product. The working standards are compared to the transfer standard to determine their accuracy. Working standards can be used to making measurements if a high degree of accuracy is required.

The measuring devices indicated in Figure 27-1-2 are used to make measurements. The accuracy of these devices

is known by their comparison with the working standard. Thus, the total hierarchy offers the provision for determining the ability of a measuring device to make a measurement in units embodied by the primary reference standard (e.g., national standard). The hierarchy permits billions of measuring devices to be compared economically with the national standard.

Standards by Adoption

Written standards in use in the United States are developed by either government agencies, professional societies, or associations representing using industries. Those developed by professional societies and user associations are frequently adopted by the National Standards Institute as a national standard. These standards may also be made mandatory for use by governmental statute or regulation. In any event, when two or more using parties agree to comply with written criteria, a standard has been adopted.

Some examples of written standards pertaining to metrology are as follows:

- Military Standard 105D, Sampling Procedures and Tables for Inspection by Attributes - This standard defines criteria and procedures for use of statistical sampling techniques.
- Department of Commerce Handbook H-28, Screw Thread Standards for Federal Services - This standard defines classes of threaded fasteners and their precision.
- Department of Commerce GGG-G-15, Gage Blocks and their Accessories - This standard defines classes of gage blocks and their accuracies.
- American National Standards Institute Y-14.5, Dimensioning, and Tolerancing - This standard defines

methods of designating form features on drawings and the interpretation of such designations.

FUNDAMENTAL CONCEPTS OF MEASUREMENTS

Concepts

Fundamental concepts and terms are used within any discipline. In metrology the primary concepts are: standards, accuracy, and precision. The secondary concepts are: readability, sensitivity, and linearity. Standards were previously introduced. Prior to introducing the other five terms, the term "measurement" will be defined and illustrated and the fundamental design of measuring devices will be reviewed.

Definition of Measurement

Measurement is the act or process of ascertaining the dimensions (or other features) of something by comparing its dimensions (or other features) to an accepted standard utilizing devices designed for that type of measurement. This means that, in order for measurement to occur, the measuring device used to gage the feature must be compared to a standard. In this manner, the measurement result has validity because the accuracy of the measuring device has been determined.

Fundamental Design of Measuring Devices

All measuring instruments or devices have common design features: sensor, transducer, and readout. Depending on the specific measuring device, the same part may serve in multiple capacities or individual parts may exist for each of these three components.

- Sensors - Sensors are the elements of instruments that detect the units to be measured. The contacts

of a micrometer are considered as the sensor in that the spacing of the contacts detects the length units being measured. Tracers of surface roughness measuring equipment are sensors of surface topography in that these tracers follow the surface contour. The sensory state of a measuring system should ensure the desired change of readout per unit of measured quantity and should also be sensitive to all required characteristics of the measured quantity.

- Transducers - The transducer is a device that responds to a given parameter to be measured by producing a signal which is related to one or more variables of that parameter. Such devices vary from the delicate and reliable transducers of space vehicle telemetry systems to the simple air gages for measuring cylinder bores.
- Readout - Readout is the indication of the measured feature in the desired units. Readout may be by direct indicating, digital or recording.

Figure 27-1-3 shows the sensor, transducer, and readout of a measuring device. Note the following features of this measuring device.

- the anvil is the sensor
- the internal lead screw functions as the transducer
- the thimble functions as the readout.

Accuracy

Accuracy is defined as the agreement of a measurement with the true value of the measurement quantity. Accuracy is the agreement of the recorded value with the value that would have been obtained had the dimension been directly compared to the primary reference standard. Recall that the primary reference standard was the most accurate technique

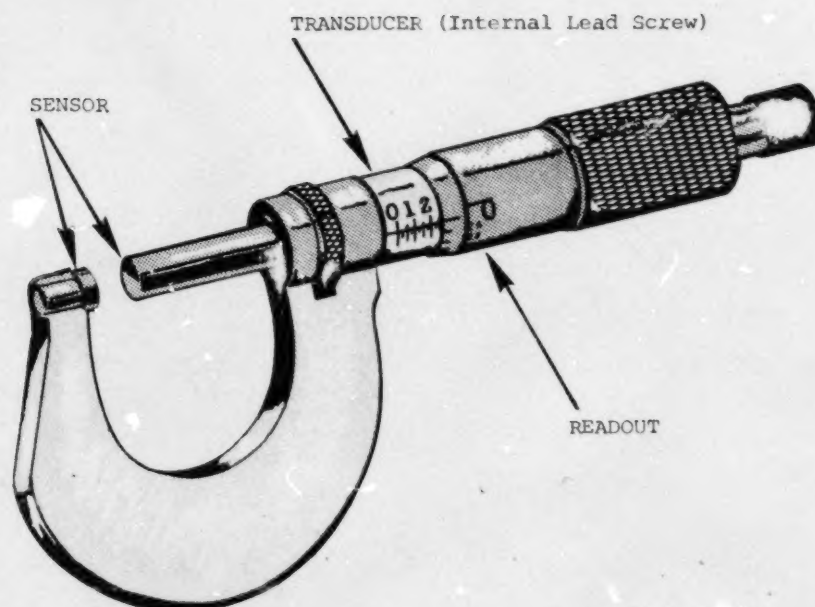


Figure 27-1-3. Illustration of Basic Design

for measurement of a given parameter. Therefore, in dimensional metrology, one is attempting to reference the accuracy of a given measurement back to this primary standard or "most accurate" measurement.

Considering only the accuracy of the measuring device and intermediate standards, the accuracy could be determined if the accuracy of each intermediate Standard were known. However, this would not account for human accuracy in using and reading the measuring device nor other factors such as temperature effects. Sources of error affecting accuracy are described later in this module. Module 27-8 describes the total measurement system as a composite of the first seven modules and, thereby, describes the predominant factors affecting accuracy.

Accuracy of measurement is essential to the ability to ensure fit, function and interchangeability. Two principles for achieving accuracy are:

- The more alike two things are, the more accurately they can be compared.
- The operations performed on the standard and the unknown must be as identical as feasible.

The first principle involving the accuracy of measurements could be demonstrated by comparing a meterstick to a yardstick of the same accuracy. Measurements involving these two devices require the use of conversion factors which introduce another source of error. It would be easier to compare one meterstick to another meterstick or a yardstick to another yardstick.

The second principle involving the accuracy of measurement advises that to achieve greater accuracy in a measurement, the same technique and the same environment should be employed when comparing a standard and an unknown.

Precision

Precision is the repeatability of the measuring process. One of the suggested activities listed for this module is that the width of a vee block be measured ten times with wood rule and then again with a steel rule. Completion of this basic measurement exercise will probably result in the recording of different values for the measured dimension. While accuracy of the measurement contributed to the results in that case, if the same individual uses the same measuring device to repeatedly measure the same dimension, a scatter of results is likely. Precision determines how closely identical values are obtained when repeating the same measurement at various intervals, or duplicating them by different instruments.

Inherent features of the measuring device and the

measurement technique and materials are the main factors affecting precision. Each measuring device has its own precision. The precision of the measurement technique (procedure) is affected by human factors, the use of different devices or materials, and environmental changes.

It should be noted that the concepts associated with standard, accuracy, and precision represent the heart of a measurement system. Measurements are unreliable if each of the three cannot be quantified for the corresponding measurement procedure. The discussion of error later in this module and the remaining modules of this course will describe standards, accuracy, and precision with respect to the types of measuring devices presented.

Secondary Concepts

The secondary concepts are just as important as the principal concepts. However, these concepts are more directly related to the measuring instruments' ability to measure to a standard with accuracy and precision. These secondary concepts are readability, sensitivity and linearity.

Readability

Readability is the susceptibility of a measuring device to having its indications (readout) converted to a meaningful number. For example, a worn out ruler whose graduations are difficult to read could not be used effectively in making an accurate measurement. Similarly a ruler which is graduated in one-eighths of an inch may be difficult to use when trying to read to the nearest one-tenth of an inch. Likewise, attempts to graduate a ruler in extremely fine increments, e.g., 0.010" or less, makes the ruler unreadable. The term readability is sometimes used interchangeably with discrimination. However, discrimination means the increments of the least significant unit on a

measuring device. One example is a scale graduated to the nearest one-tenth of an inch. This scale could not be used to make measurements to the nearest one-hundredth of an inch because it would not have sufficient discrimination. Readability refers to the ability of the user to read to the smallest unit on the measuring device using specified inspection procedures. Line-graduated measuring devices that have very fine discrimination may not be very readable.

Factors affecting readability of a measuring device are:

- the skill of the user
- the clarity of the readout on the instrument
- the type of readout, e.g., scale, numeric display, digital
- the level of lighting.

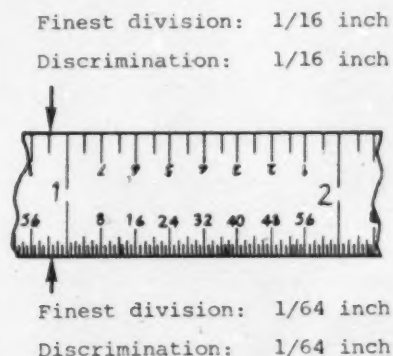


Figure 27-1-4. Readability and Discrimination

The lower scale in Figure 27-1-4 discriminates to 1/64 of an inch while the upper scale can only reliably discriminate to 1/16 of an inch. The readability of the upper scale is greater than that of the lower scale, i.e., it is easier to see the divisions.

Readability affects the selection of the measuring device to be used. Tolerance of the dimension to be measured

governs such selection. (Tolerance is defined as the range or limit of measurement values that are acceptable to the specified standard.) For example, if the tolerance of the feature of a part is plus or minus 0.125 inch, an ordinary scale or steel rule is suitable. If that same feature has a tolerance of plus or minus 0.005 inch, a vernier with a readout in increments of 0.001 inch should be considered.

Tolerance-to-Readability Ratio

Tolerance-to-readability ratio determines the selection of a measuring device for a specific application. There are two rules with respect to tolerance-to-readability ratio. One is to select instruments having at least a 10 to 1 ratio and the other is to select instruments having at least a 4 to 1 ratio. While the 10 to 1 rule is more conservative, it frequently becomes impractical when calibrating instruments. When the 10 to 1 rule is applied to the hierarchy of standards in the calibration process, the "state-of-the art" of inspection capability is often exceeded. Hence, the 4 to 1 rule is more practicable. For fixed limit tolerances, readability becomes a factor as the limit is approached. Examples of both rules for selection of measuring devices are given in Table 27-1-3.

Sensitivity

Sensitivity is the ability of a measuring device to detect differences in a quantity being measured. For example, if the device will detect differences of 0.0002 inch in measured values, its sensitivity is 0.0002 inch. Typical sensitivities of commonly used measuring devices are given in Table 27-1-4.

Table 27-1-3. Examples of 10/1 and 4/1 for Selection of Instruments

Size	Tolerance	Minimum Readability of Instrument	
		10 to 1 Rule	4 to 1 Rule
6.50 ± .05	0.10	0.01	0.025
3.250 ± 0.001	0.002	0.0002	0.0005
5.5000 ± 0.0001	0.0002	0.00002	0.00005
8.750 Maximum	Maximum Limit	0.01 Below 8.740	0.025 Below 8.740
		0.001 Between 8.740 and 8.749	0.0025 Between 8.740 and 8.749
		0.0001 Between 8.749 and 8.750	0.00025 Between 8.749 and 8.750

Table 27-1-4. Measuring Sensitivities in General

TYPE OF MEASURING DEVICE	TYPICAL SENSITIVITY	TYPE OF MEASURING DEVICE	TYPICAL SENSITIVITY
Line Graduated Rules and Tapes	1/32 or 1/64 inch	Vernier Caliper	0.0001 inch
Micrometer Without Vernier	0.001 inch	Micrometer with Vernier	0.0001 inch
Bevel Protractor Without Vernier	1 Degree	Bevel Protractor with Vernier	5 Minutes
Mechanical (Dial) Indicators	From 0.00005 to 0.0001 inch	Electronic Comparators	From 0.000 001 to 0.0001 inch

Factors affecting sensitivity include:

- the ability to dampen an instrument. (Dampening refers to a process of reducing an instruments' tendency to "hunt" for the measurement value. This can be a particular problem with instruments using an electronic readout.)
- the degree of drift of electronic or pneumatic gages.
- the skill of the user.
- the overall precision of the measuring device.
- environmental effects. Sensitivity may be affected by ambient temperature, humidity, and corrosiveness of the environment.

Selection of the measuring device to be used with respect to sensitivity is based on tolerance and environmental conditions. The 4 to 1 rule applicable to readability applies to sensitivity. That is, if the measuring device has a sensitivity of 25% of the tolerance, it is a suitable device.

Linearity

Linearity is the agreement of the measurement throughout the full range of any given measuring device with the true incremental unit increases of the unit being measured. Linearity can be envisioned as the change in accuracy over the range of the measuring device. For example, Figure 27-1-5 shows an example of a linear scale and a non-linear scale.

Linearity involves the precise spatial relationship of markings of readout on the instrument and the ability of the instrument to proportionally transmit variations in value of the feature from the sensor to the readout. For example, the linearity of a clock is affected by the spatial relationship of the dial markings and the ability of the clock's mechanism to drive the hands through each

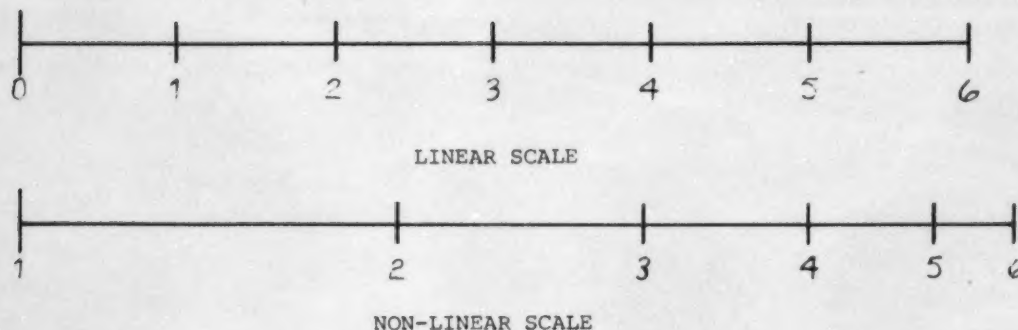


Figure 27-1-5. Examples of Linear and Non-Linear Scales

increment of marking in the same time period.

Linearity of an instrument is affected by:

- Manufacturing tolerances in making the instrument.
- Design of the instrument, for example, certain types of instruments contain features which are inherently non-linear and compensatory measures are included in the design.
- Wear or deterioration of the transmitting or amplifying device from sensor to readout.

Linearity of an instrument is best determined by comparison with standards representing increments of the range of the instrument. This feature of a measuring device is normally checked during "calibration", that is, when it is compared and adjusted to standards. Linearity becomes suspect when measurements by one instrument cannot be repeated with expected precision by another same or equivalent type of instrument.

ERROR OF MEASUREMENT

Error

The difference between the measured value and the true value is the error. Except for unusual cases, the inspector never knows an absolutely *true value*. One must always assume that there is some error in a given measurement. When a measurement is repeated the results will disagree by an amount called the *discrepancy*. The causes of discrepancy must also be the causes of differences between the readings and the true value.

Error can be positive or negative, that is, the measurement value may be either side of the true value. All measurements have some error. The objective of the metrology program is to provide sufficient accuracy to ensure fit, function, and interchangeability.

Types of Error

Errors are typically categorized as random or systematic. Random errors are primarily associated with the human element and result from inaccurate readings and calculation, improper use of instruments, and errors in recording values. Such errors are difficult to predict, but can be evaluated statistically from past results. The smaller the *random* errors, the greater the precision. Systematic errors are those which are generally controllable or measurable. They include the instrument's capabilities, environmental condition, and procedural techniques. In other words, if all of the individual readings are the same it does not mean that there are no errors. They could all vary from the true value by a uniform or *systematic error*. A good example is a kink in a steel tape. All measurements that include the kink will have the same amount of positive

error. They will be too long. As the value of *systematic* errors decreases, accuracy increases. Experience shows that most measurements contain a combination of both random and systematic errors.

Sources of Error

Error of measurement is the composite effect of all sources of error. These sources of error may be subtle and require painstaking research to locate within the measurement procedure. However, each measurement procedure is susceptible to error from six sources. These sources are the measuring device, the operator, a group of operators, materials, procedure, and laboratory.

- Errors of the Measuring Device - Errors may exist in a specific measuring device or between like types of measuring devices. The errors are associated with nonlinearity, imprecision, instability or drift, and sensitivity to features other than that being measured. For example, temperature, electromagnetic fields, electrostatic fields, and vibration. Also, when use of the measuring device involves supplementary apparatus, sources of error include the precision of locating the apparatus, the tightness of mechanical joints and the conductance of electrical connections.
- Errors of an Individual Operator - A single individual obtains diverse results in repeating the same inspection procedure. This type of *Human error* is particularly difficult to detect when a person tries to evaluate himself or herself. Human errors include common things as a tendency to read high, or low. Error sources are generally related to the capacity and skill of the individual, the human state of imperfection (inadvertent errors), and conditions that foster willful errors. With respect to willful

errors, insufficient allotment of time for inspection or some other pressure to accept product regardless of consequence may result in an inspector willfully biasing his or her techniques or results. Human errors are usually remedied as soon as they are disclosed. Personnel training is the best means of prevention of human errors.

- Errors among Operators - These are the human-related sources compounded by the number of inspectors. Two inspectors inspecting the same dimension generally obtain different results. The magnitude of such differences is proportional to the complexity of the inspection procedure. Therefore, human errors generally change with the change in observers. This is usually both due to their existence and the means for their detection.
- Errors of Materials - In those measurement systems where materials are partially consumed or deteriorate with time, errors creep in. Examples include the hardness calibration block that is partially consumed with each hardness test and the deterioration of electronic parts.
- Errors of Procedure - Each variation permitted by the inspection procedure is a possible source of error. Variations may arise from the procedure permitting the inspector to use judgment on selection of the measuring device, specific techniques for using the measuring device, and positioning or manipulation of the item to be measured. For example, if a technique developed to calibrate vernier instruments is used to calibrate micrometers, the results will have an uncertainty because the technique is not appropriate. In addition, variations may also be in the form of options spelled out in the procedure

- or by the procedure specifying ranges of conditions that affect the instrument's accuracy and precision.
- Errors of Laboratory - The sources of errors listed above may be present in calibration laboratories. Each organization's calibration laboratory is susceptible to some degree of error. Also, variations of laboratory practices are possible.

Reduction of Error

If error is to be reduced, sources of error must be isolated and quantified. Elaborate test methods beyond the scope of this course are often required. While all sources of error must be considered, a specific measurement normally has only a few sources of error of sufficient magnitude to significantly affect the measurement.

As an illustration of quantified error, the precision of a hypothetical instrument is explored. Table 27-1-5 gives the results of a measurement repeated 20 times by the same instrument under the same condition with all other factors held constant. If the true value of a given parameter is 0.050, then the difference between the average of the measured values and the true value of the dimension is the error. The standard deviation of the measured values is the precision. The standard deviation is an indication of how widely the measured values are dispersed about the average measured value. Module 27-7 of this course will consider the standard deviation concept more completely. For the present, it is sufficient to say that if one computed the standard deviation for the 20 measurements listed in Table 27-1-5, its value would be 0.00176. This is a measure of just how precise the measurement is.

For purposes of illustration, then, simply consider the measured data in Table 27-1-5 as an example of determining the average measured value in comparison to the true value.

Table 27-1-5. Example of Accuracy and Precision

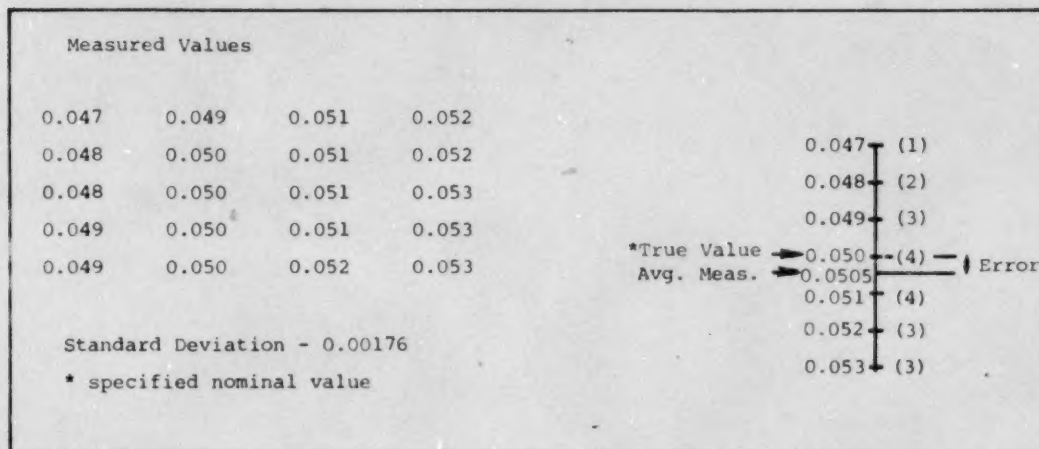


Table 27-1-5 indicates that, on the average, the instrument is inaccurate by 0.0005 inch on the high side of the true value. Calibration of the instrument to a standard would reduce this error. However, the precision is a function of the design of the instrument that calibration would not affect. Table 27-1-5 indicates that 55% of the time the instrument will repeat a measurement within one standard deviation. In this example, the instrument is fairly accurate but has poor precision.

TEMPERATURE EFFECTS

Rules for Measurements

The universally accepted standard measurement temperature is 68°F for measurement of dimensions. As measurements are made at temperatures departing from 68°F, error is introduced if differences exist in the thermal expansion of the measuring device and the item being measured. Consequently, when measurements are made at other than 68°F, the magnitude of the error is determined and, if necessary,

the measurement result is corrected to account for this error. Three rules apply with respect to temperature effects on the accuracy of a measurement:

- Both the measuring device and the item to be measured must be at the same temperature.
- Measurements at 68°F do not require correction for temperature effects.
- Measurements at other than 68°F require calculation of temperature effects to determine if the magnitude of error is sufficient to warrant correction of the measured value.

Magnitude of Temperature Effects

The magnitude of the temperature effect is directly proportional to the difference in the thermal expansion coefficients of the measuring device and the item to be measured and to the amount of departure from 68°F. The temperature coefficient indicates that fraction of an inch by which each inch of length of a material changes for each degree of temperature change. Since each specific alloy has its own unique thermal expansion coefficient, the specific alloys of the measuring device and the item to be measured must be known.

For illustrative purposes only, average values of thermal expansion coefficients for some common materials are shown in Table 27-1-6. For on the job calculations, real coefficients must be used for the specific type and grade of materials. Metals handbooks and similar reference books give thermal expansion coefficients. In using these on-the-job, one should take care to ensure use of coefficients for the specific type and grade of material involved in the measurement.

Table 27-1-6. Average Thermal Expansion Coefficients

MATERIAL	COEFFICIENT
Tool Steel	6.4×10^{-6} inch/inch/ $^{\circ}\text{F}$
Stainless Steel (410)	5.5×10^{-6} inch/inch/ $^{\circ}\text{F}$
Tungsten Carbide	3.0×10^{-6} inch/inch/ $^{\circ}\text{F}$
Chromium Carbide	4.5×10^{-6} inch/inch/ $^{\circ}\text{F}$
Copper	9.4×10^{-6} inch/inch/ $^{\circ}\text{F}$
Aluminum	12.8×10^{-6} inch/inch/ $^{\circ}\text{F}$

As mentioned earlier, the values given in Table 27-1-6 are the average thermal expansion coefficients for various materials. On the job, it is necessary to calculate the effects of temperature on the accuracy of linear measurements, using the real coefficient for the specific type and grade of material. Temperature effects on the accuracy of linear measurements are calculated by the following formula:

$$MD = L (k_g - k_w) (T - 68^{\circ}\text{F}) \quad \text{Equation 27-1-1}$$

Where:

MD = measuring difference in inches of the measurement at temperature as compared to the same measurement at 68°F .

L = length of the measurement in inches.

k_g = thermal expansion coefficient of the measuring device in inch per inch of length per $^{\circ}\text{F}$.

k_w = thermal expansion coefficient of the workpiece in inch per inch of length per $^{\circ}\text{F}$.

T = temperature in $^{\circ}\text{F}$ at which the measurement is made.

EXAMPLE:

Problem: What is the value of the measurement corrected to 68°F ?

Given: A measurement at 58°F of an aluminum bar with a steel device reads 84.125 inches.

Solution:

$$\begin{aligned} MD &= L (k_g - k_w) (T - 68^{\circ}\text{F}) \\ &= 84.125 (6.4 \times 10^{-6} - 12.8 \times 10^{-6}) (58 - 68) \\ &= 84.125 (-6.4 \times 10^{-6}) (-10) \\ &= 5384 \times 10^{-6} \text{ inch} = 0.005384 \text{ inch} \\ \text{value at } 68^{\circ}\text{F} &= 84.125 + 0.005 \\ &= 84.130 \text{ inches} \end{aligned}$$

NOTE: If MD is a negative value, it is subtracted from L.

CLEANLINESS

Importance of Cleanliness

Cleanliness is absolutely necessary if accurate dimensional inspection is to be achieved. Both the measuring device and the item to be inspected must be clean. Otherwise, accuracy and precision of the measurements are affected. The concern for this effect increases as the need for accuracy increases. For example, cleanliness is a larger factor when accuracy must be within 0.001 inch than when it must be within 0.010 inch.

Sources of errors from a cleanliness viewpoint include dirt, lint, scale, rust, oil, grease, paint, ink or chalk markings, and any other loose surface materials. Where highly accurate measurements are required on an on-going basis, clean rooms are established to maintain a state of cleanliness. Such clean rooms are enclosed and have filtered air supplies and a schedule for cleaning all surfaces. Temperature and humidity control are also normally provided in clean rooms. Where such high accuracy is necessary but the item cannot be transported to a clean room, a temporary clean room or area is constructed around the item. Regardless of whether a clean room is used, *measuring devices and items to be inspected are always cleaned prior to inspection.* (CAUTION: Cleaning may cool the items; time should be allowed for temperature equalization.)

CARE AND HANDLING OF INSTRUMENTS

Importance

Proper care and use of instruments cannot be stressed enough. The various gages are sensitive instruments whose accuracy is adversely affected by abuse. All users of gages must properly use and care for gages and when an

instrument is inadvertantly mishandled, turn it in to the calibration laboratory for checking and recalibration.

Guidelines for Care and Handling

Users of instruments must know how to properly handle and care for the instrument in order to maintain it in its "calibrated" condition. Regardless of the type of instrument, the following guidelines provide for proper care and handling:

- Use the instrument only for the purposes for which it is intended.
- Never use any manipulative device or force the instrument.
- Clean and remove burrs prior to use.
- Never expose an instrument directly to heat.
- When an instrument has been exposed to heat, be sure the expansion caused by heat does not exceed tolerance.
- Avoid exposure to dust, moisture, and grease,
- Lightly oil instruments and store in a protected case or cabinet.
- Return all instruments to storage case or cabinet after use.



EXERCISES

Briefly explain or discuss each of the following concepts covered in this module:

1. Metrology is a science of measurement that is absolutely necessary to insure the fit, function and interchangeability of product.
2. Measurement is impossible without standards.
3. Standards are the embodiment or true value of units of measurement and the written criteria governing an inspection procedure.
4. Transfer and working standards permit all organizations making measurements to employ standards which are traceable to the primary reference standards of the U.S. National Bureau of Standards.
5. The principal concepts associated with measurement are standards, accuracy and precision.
6. The accuracy of a specific measuring device is a function of its design and its readability, sensitivity and linearity.
7. The 4 to 1 rule states that the measuring device should have discrimination and sensitivity that is no more than 25% of the tolerance of the dimension to be measured.
8. Error can stem from any portion of the measurement procedure. Normally, only one or two sources of error are of such magnitude as to be of significant concern.
9. Accuracy and precision of measurement are directly proportional to the state of cleanliness of the instrument and the item to be measured.
10. Three rules apply to measurements with respect to temperature effects:
 - a. Both the measuring device and item to be measured must be the same temperature.

- b. Measurements at 68°F do not require correction for temperature effects.
 - c. Measurements at other than 68°F require calculation of temperature effects to determine if the magnitude of error is sufficient to warrant correction of the measured value.
11. For linear measurements, the temperature effects are calculated by the formula $MD = L (k_g - k_w) (T - 68^\circ F)$.



MATERIALS

The following materials are required to support this module:

1. Laboratory Vee Blocks
2. Steel Rules (12 inches minimum)
3. Wood Rules (12 inches minimum)
4. Length Standard (gage block set or calibrated scale)



PROCEDURES

The following activities reinforce the information presented in this module:

Given:

Laboratory Vee Block
12 inch Steel Rule
12 inch Wood Rule

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Perform the following:

1. Measure the width of the Vee Block ten times each with wood and steel rules. Record values in a table.
2. Calculate the average value of each set of ten readings

$$\bar{x} = \frac{x_1 + x_2 + \text{-----}x_{10}}{10}$$

3. Measure the width of the Vee Block using different sections of the rule. For example, if the 0 to 4 inch portion was initially used, measure with the 4 to 8 inch and 8 to 12 inch portions. Record any differences from the initial values.
4. From the initial measurements, state possible reasons for any of the following conditions that resulted:
 - Differences between readings of the steel rule and the wood rule.
 - Differences in readings of the same rule.
5. Compare the steel rule to a standard (either another steel rule or a gage block). State similarities and differences.
6. Compare the measurements obtained in step 1 with those obtained in step 3. State similarities and differences and describe linearity of the rule.
7. List the factors that affect the rules' readability and sensitivity.
8. Describe the primary standard, the transfer standard and the working standard for the measuring device you have used.



DATA TABLE

Data Table 27-1-1

Measurement of Vee Block

	Measurements with Wood Rule	Measurements with Steel Rule	Other Measurements
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			
9.			
10.			
Sum			
Average			

Description of Reason for Differences in Measurements: _____

Comparison of Steel Rule with Standard: _____

Linearity of Rule: _____

Description of Standards: _____



REFERENCE MATERIALS

- Brown and Sharpe Mfg. Co., Principles and Practice of Precision Measurement, Brown and Sharpe Mfg. Co., Precision Park, North Kingstown, RI, 1975
- Busch, Ted, Fundamentals of Dimensional Metrology, Delmar Publishers, Third Edition, 1966
- Farago, Francis T., PhD, Handbook of Dimensional Measurement, Industrial Press Inc., Third Printing, 1968
- International Business Machines Corp., Precision Measurement in the Metal Working Industry, Syracuse University Press, Syracuse, N.Y. Seventh Printing, 1969
- J.M. Juran, Quality Control Handbook, McGraw-Hill Book Company, New York, N.Y., Third Edition, 1974
- Society of Manufacturing Engineers (SME), Handbook of Industrial Metrology, Prentice-Hall, Inc., 1967
- U.S. Department of Commerce, Letter Circular LC1035, Units and Systems of Weights and Measures; Their Origin, Development and Present Status, National Bureau of Standards, Washington, D.C. 20234



TEST

Define the following:

1. Standard:

Accuracy:

Linearity:

Sensitivity:

Readability:

Precision:

Measurement:

2. Why is it necessary for metrology to be applied to the design, construction and operation of nuclear power plants?

3. Briefly describe each of the following standards and name the type standard to which each is compared for accuracy.

a. Working Standards:

b. Primary Reference Standards:

c. Transfer Standards:

d. Measuring Instruments & Equipment:

4. Why are standards important to measurement? How are standards adopted?
5. Name and state the major function of the three common design features that all measuring instruments or devices have.
 - a.
 - b.
 - c.
6. Why is accuracy an important characteristic of a measuring device? What two principles govern the accuracy of a measurement?
7. Name four factors that affect the precision of a measurement process.
 - a.
 - b.
 - c.
 - d.
8. What is tolerance? Why is the tolerance-to-readability ratio used?
9. Name four factors that affect the sensitivity of a measuring instrument.
 - a.
 - b.
 - c.
 - d.

10. Name three factors that affect a measuring instrument's linearity.
 - a.
 - b.
 - c.
11. Name two factors that affect a measuring device's readability.
 - a.
 - b.
12. Name six sources of errors of measurement. Describe the factors that contribute to each source of error.
 - a.
 - b.
 - c.
 - d.
 - e.
 - f.
13. Why is it necessary to calculate temperature effects when measurements are made at temperatures above or below 68°F?

14. Find the value of the measurement, corrected to 68°F, given the following (use the average thermal expansion coefficient of 9.4×10^{-6} inch/inch/°F for copper and 6.4×10^{-6} inch/inch/°F for tool steel).

Feature: length of copper spacer bar

Instrument: tool steel outside micrometer

Temperature: 83°F

Measured Value: 12.4485 inches

Use the scale below to give the value, in inches, of questions 15-21.

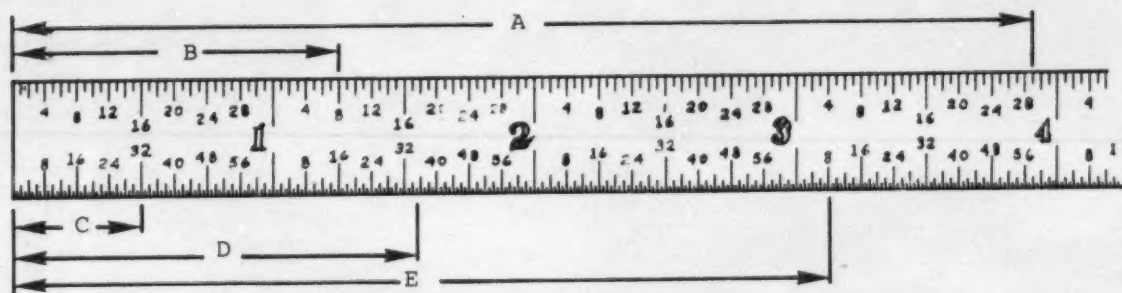


Figure 27-1-6

15. Discrimination of top scale _____
16. Discrimination of bottom scale _____
17. A length = _____
18. B length = _____
19. C length = _____
20. D length = _____
21. E length = _____